BEDLOAD TRANSPORT RATES AT NEAR-BANKFULL FLOWS IN A STEP-POOL CHANNEL

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Abstract: This paper examines unit bedload transport rates (BTRs) at near-bankfull flows within a small step-pool channel in the Ouachita Mountains of central Arkansas. For this study, five runoff events with peak discharges between 0.25 and 1.34 cms (1.0- to 1.6-yr recurrence intervals) were produced in a natural channel using a streamflow simulation system. BTRs range from 3.5×10^{-6} to 3.3×10^{-2} kg/sec/m during these events and are somewhat lower in magnitude than those reported previously for step-pool channels. BTR behavior is best modeled using discharge, but the relationship differs significantly between events with peak flows less than 0.61 cms (1.1 yr) and those greater than 0.88 cms, (1.2 yr). The smaller events exhibit higher BTRs than the larger events at flows from 0.11 to 0.35 cms, but similar rates at higher discharges. Slope coefficients are within the range Ryan and Troendle (1996) determined for two step-pool sites in Colorado. BTRs show similar positive relationships to both shear stress and stream power, but these relationships are weaker than the one with discharge. These results support the idea that sediment availability limits BTRs in step-pool channels.

INTRODUCTION

Bedload transport rates (BTRs) have received only limited study in step-pool channels. Reported maximum rates are highly variable, ranging from 0.30 (Ryan 1994) to 1.67 kg/sec/m (Hayward 1980), and often appearing to be controlled as much by local conditions as hydraulic factors. The relationship of BTR to discharge has been examined most often (e.g., Nanson 1974, Hayward 1980, Ashida and others 1981, Ketcheson 1986, Ryan and Troendle 1996), but results are often confounded by differences in antecedent conditions (e.g., sediment supply or the magnitude and number of previous events). Its relationship to other hydraulic forces has only been assessed in a few studies (Warburton 1992, Blizard and Wohl 1998).

This paper examines BTRs in a step-pool channel during simulated, near-bankfull streamflow events and controlled antecedent conditions. It documents BTR ranges and how these compare with previously reported values. It also examines relationships between BTRs and discharge, shear stress, and stream power, and discusses factors that can explain observed BTR characteristics.

METHODS

A typical step-pool reach located within the Ouachita Mountains near Hollis, Arkansas was used for this study. This reach is located on an unnamed tributary of Little Bear Cr and is hereafter referred to as Toots Cr. Annual precipitation averages 130 cm, occurring almost entirely as rain, and streamflows are ephemeral to intermittent. The catchment area above the study reach is 39 ha with an overall relief of 140 m and hillslopes ranging from 15 to 30%. Vegetation is predominantly composed of a shortleaf pine (*Pinus echinata Mill.*) overstory and a mixed hardwood understory including white oak (*Quercus alba L.*), red oak (*Q. rubra L.*), and various hickories (*Carya* spp.) (Marion and Malanson in press). Within the 100-m study reach, the channel has a weighted (by channel length) mean gradient of 8.8%. Banks are composed of mixed colluvial and alluvial deposits while surface bed material ranges from silts to boulders with an overall D_{50} of 56 mm. Bankfull widths average 4.2 m.

Five individual flow events with peak discharges ranging from 0.25 to 1.34 m^3/sec (1.0- to 1.6-yr recurrence intervals) were simulated. Bankfull discharge was estimated to be 1.11 m^3/sec (1.4-yr recurrence interval) from channel features and computed hydraulic values. All flow events were created using controlled releases from a storage tank (see Marion and Weirich 1997 for details on system operation). Events were produced on five consecutive days and sequenced so that Event 1 had the smallest peak flow while Event 5 had the largest (Figure 1).

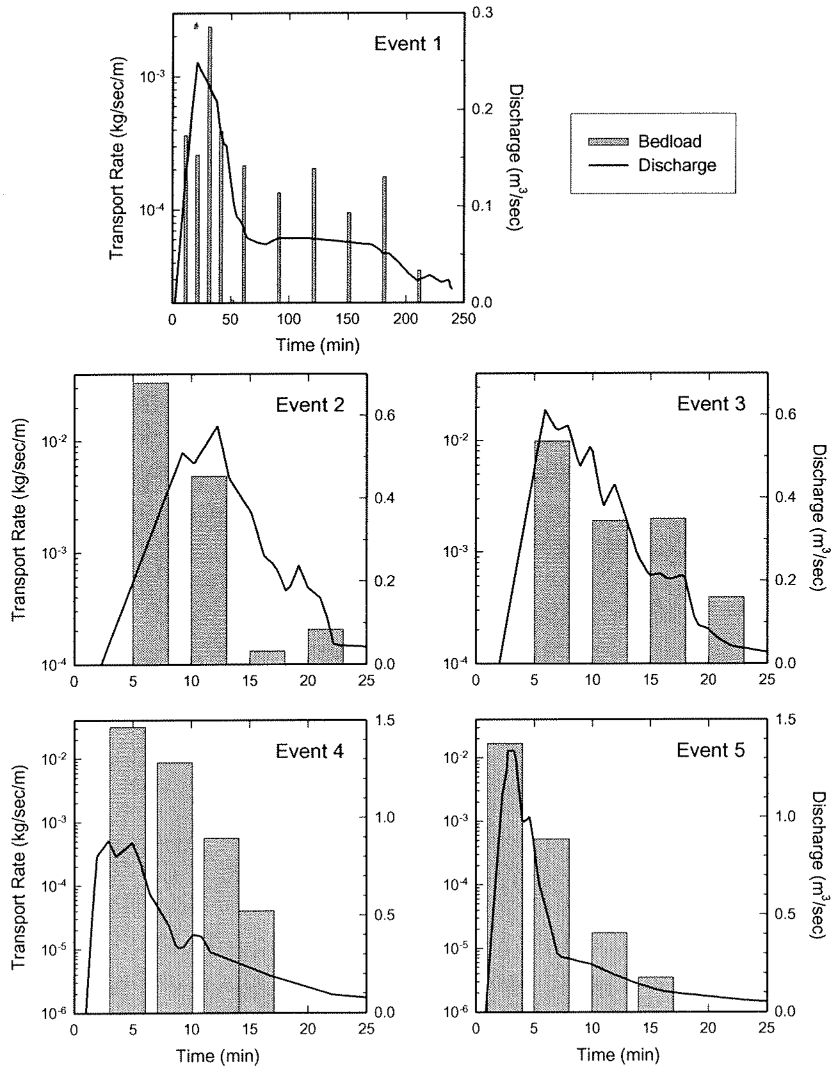

Figure 1. Bedload transport rates and discharges during Toots Cr events. Bar width equivalent to 3-minute sampling interval.

BTRs were measured using a standard 76-mm Helley-Smith sampler (Helley and Smith 1971). Throughout each event, samples were taken for 1-min intervals at three fixed locations across a sampling bridge to produce a composite sample for each measurement time. Bedload was also measured for each event using a pit trap installed at the downstream end of the study reach. Samples were oven dried and passed through a one-f sieve series from 0.062 to 16.0 mm. Larger grains were measured individually.

Bedload tracers, channel cross-sections, and bed erosion pins were also used to assess bed material entrainment, scour, and fill. Seventy-three bed clasts between 16 and 256 mm were randomly selected, marked, and re-installed within the study reach. Cross-sections were monitored at three channel locations and erosion pins were installed in all fine-sediment bed patches (Marion and Weirich 1999). All devices were measured prior to Event 1 and after each subsequent event. The channel was also visually inspected at the same times to identify any localized changes in erosion or storage.

RESULTS

BTRs from Helley-Smith samples are shown in Figure 1. BTRs range from 3.5×10^{-6} to 3.3×10^{-2} kg/sec/m during the five events. Maximum BTRs do not do not vary consistently with event magnitude. Events 2 and 4 exhibit the largest maximum BTRs. In both cases, the events that immediately followed had either equivalent (Event 3) or somewhat greater (Event 5) flows, but had markedly lower maximum BTRs.

Overall, Toots Cr BTRs are somewhat lower in magnitude than those that have been reported previously for step-pool channels. Their range is shown in Figure 2 along with BTR and corresponding discharge ranges for several small mountain streams. Toots Cr BTRs span the lower to middle portion of the overall range defined by the five step-pool sites. Differences from other sites may be partially due to hydraulic differences and measurement methods. Larger BTRs generally occur at sites having greater discharges. Also, the studies with the two largest BTRs both measured bedload using traps, whereas the other studies used Helley-Smith samplers.

BTRs determined at Toots Cr using the 73-mm Helley-Smith sampler may be low. Maxima for the coarsest Helley-Smith samples are consistently smaller than those measured with both the bedload trap and tracers (see Table 1). These differences are most likely due to the limitations of the Helley-Smith sampler which excludes grains approaching or greater than its orifice size and has less opportunity to catch larger grains due to the limited time it is deployed in any given spot.

Table 1. Maximum bedload sizes by measurement method and percent of tracers displaced for Toots Cr events. The coarsest Helley-Smith samples are used for each event and measured to the nearest f -size class.

Event	Maximum Size Displaced (mm)			Percent of Tracers Displaced
	Helley-Smith	Bedload Trap	Tracers	
1	16-32	67	123	16
2	64-128	156	170	7
3	16-32	74	38	2
4	32-64	132	130	10
5	32-64	75	180	15

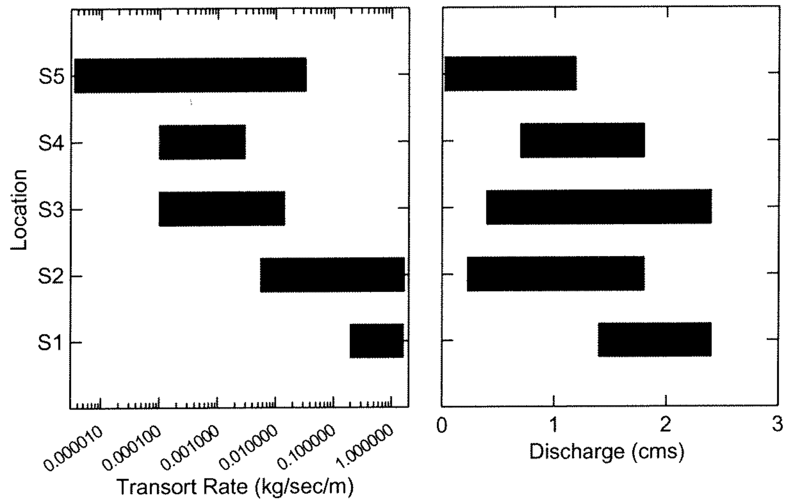

Figure 2. Bedload transport ranges and corresponding discharges for step-pool channels. Sources: S1 = Takahashi and Sawada, S2 = Hayward 1980, S3–S4 = Ryan 1994, S5 = this study.

Any bedload exclusion would reduce the computed BTR, but this is especially true for the largest sizes in which a small number of grains account for much of the total sample mass.

BTRs generally increase with increasing discharge. However, as evident from Figure 3, the relationships between BTR and discharge are different for events with peak discharges less than 0.71 cms (Events 1–3) and those with higher values (Events 4–5). Results using a General Linear Model and the Bonferroni multiple comparison test (Milliken and Johnson 1984) clearly indicate that BTR response to increased discharge is similar in Events 1–3 or Events 4–5, but that there are significant differences ($P = 0.04$) between these event groups. Model statistics are listed in Table 2. According to these results, BTRs during Events 1–3 at low to moderate discharges (0.11–0.35 cms) are much higher than during Events 4 and 5. Plots of the two models (Figure 3) suggest that the apparent differences may disappear at discharges greater than 0.35 cms (~ 1.05-yr event).

Several authors have noted significant relationships between BTR and discharge in step-pool channels (Nanson 1974, Ketcheson 1986, Blizard and Wohl 1998), however only Ryan and Troendle (1996) report their results in units that allow comparison to the Toots Cr findings. Using the same model form as here, Ryan and Troendle obtained exponents of 2.13 and 2.24 for two sites during two snowmelt seasons. These fall between the exponents obtained for Toots Cr (see Table 2). Their b_0 values (5.5×10^{-4} and 3.4×10^{-4}, respectively) are smaller than those for Toots Cr. Their model R^2 values were also comparable (0.79 and 0.44).

Neither bed shear stress nor cross-sectional stream power explain BTR change better than discharge for the five events. Both were analyzed using the same methods as for discharge and both were found to show clear differences between the same event groups as does discharge (all $P < 0.02$). The resulting models for shear stress and stream power are listed in Table 2.

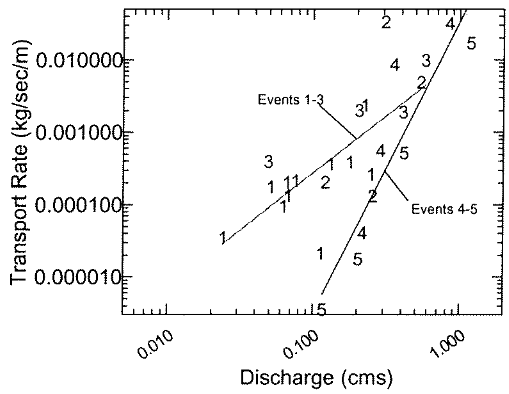

Figure 3. Relationship between bedload transport rates and discharge for Toots Cr events. Symbols indicate event numbers.

Blizard and Wohl (1998) found significant relationships (a = 0.05) between BTR and both shear stress and stream power at two of three sites on East St. Louis Cr in the Colorado Rocky Mountains. Their data were taken throughout one snowmelt season, not individual events like at Toots Cr. They used mean stream power (after Rhoads 1987) rather than cross-sectional stream power. They analyzed these relationships using both at-a-point data and data averaged over entire cross-sections, the latter being the same as done for Toots Cr. Blizard and Wohl found mean cross-section values for both shear stress and stream power to be somewhat more successful than at-a-point values at modeling BTR change, but did not report model R^2 values.

Table 2. Model statistics for predicting bedload transport rate (kg/sec/m) during Toots Cr events. Sample sizes are 19 for Events 1–3 and 8 for Events 4–5. Model form: $y = b_0 \cdot x^{b1}$.

Independent Variable	Event Group	b_0	b_1	R^2
Discharge (cms)	1–3	1.05×10^{-2}	1.58	0.54
	4–5	3.43×10^{-2}	4.04	0.84
Shear stress (N/m^2)	1–3	1.38×10^{-1}	1.22	0.27
	4–5	9.82×10^{-4}	5.59	0.79
Stream power (W/m)	1–3	1.26×10^{-4}	0.80	0.32
	4–5	2.11×10^{-9}	3.46	0.84

DISCUSSION

Two aspects of the results seem problematic. The first is that BTR relationships with hydraulic factors vary between Events 1–3 and Events 4–5. The second is that maximum BTRs varied markedly between events that are equivalent (Events 2 and 3) or similar (Event 4 and 5). The magnitude of BTRs is controlled by (1) the competency of the flow that occurs, (2) the amount of sediment in the bed that the flow is competent to transport, and (3) any restrictions on the exposure of these grains to the tractive forces inherent in the flow. Differences in BTRs between events can be ascribed to differences in one or more of these factors.

Flow competency differences between equivalent or similar events do not appear to be sufficient to explain the patterns noted above. As evident from Table 1, all events were capable of transporting up to small-cobble (64–128 mm) grains. Competency may have decreased during Event 3 relative to Event 2, which might explain the difference in maximum BTRs, but certainly did not in Event 5. In general all events transported D_{max} sizes that are roughly equivalent.

A reduction in the amount of smaller bed material between Events 1–3 and 4–5 could explain the difference in BTRs at low to moderate flows, however such a reduction does not seem likely. During Events 1–3, the majority of bedload that moved at discharges up to 0.35 cms was less than 7 mm. While overall bed size composition was not remeasured after each event, fine-sediment patches in the bed and channel cross-sections were remeasured. Previously, Marion and Weirich (1999) reported that patches exhibited net filling during all events including Events 4 and 5, while cross-sections exhibited little change. Not reported, but relevant here is that through all five events the bed material at both patches and cross-sections showed no signs of coarsening and grains less than 7 mm remained abundant. These findings and observations suggest that sediment less than 7 mm did not decrease in amount during Events 4 and 5.

The most probable explanation of BTR differences is that bed conditions evolve during each event that restrict how much sediment, especially the smaller grains, is available to be entrained. Laronne and Carson (1976) observed that smaller grains had infilled gaps within larger-grain particle clusters (e.g., steps) after peak flows within a step-pool channel. Such infilling can tighten grain packing and reduce the fine-sediment exposure to tractive forces. This bed restructuring probably occurred during all events. In this way, the amount of finer sediment would not change in the bed, but its availability during a given flow event might vary depending on the size of previous events.

The sporadic nature of bed material entrainment in coarse, heterogeneous substrates provides the mechanism by which flow competency can remain unchanged yetBTRs can vary greatly. Parker and others (1982) observed that only a very small number of the larger grains actually move in any given event. Small- to large-cobble grains (< 256 mm) were transported during all events at Toots Cr (Table 1). However, the low percentage of tracer displacements (Tables 1) and lack of pronounced cross-section changes (Marion and Weirich 1999) suggest that such entrainment occurred discontinuously throughout the reach. If finer sediment is not exposed when larger grains move, then BTRs might actually decrease even though flow competency (as represented by bedload D_{max}) remains the same.

Thus, changes in finer-sediment availability during the five events can explain both the BTR variation between Events 1–3 and 4–5, and the difference in maximum BTRs between similar events. In the case of the former, at peak Event 4 and 5 discharges, BTRs were relatively high (Figure 1) as larger grains were mobilized. However, subsequent flows at moderate to low hydraulic force levels encountered a better-organized bed with less finer sediment available than during Events 1–3, and lower BTRs resulted. In the case of the latter, differences in peak BTRs are possible if both larger bedload were entrained *and* new finer-sediment sources were briefly exposed during peak discharge for Events 2 and 4, but both conditions did not occur during Event 3 and 5 peak discharges. The sediment sources that produced Event 2 and 4 peak BTRs may have occurred at locations that were not replenished during recession flows. If so, then Events 3 and 5 would have to either displace more or larger particles, or exploit new finer-sediment sources to produce equivalent BTRs.

Others have concluded that limits on sediment supply are the most likely cause for reduced BTRs during constant or increasing flows in step-pool channels. Nanson (1974) found restricted sediment supply the best explanation for declining BTRs during high discharges after the snowmelt peak flow. Ashida and others (1976) also reasoned that limited sediment storage explained numerous observations of declining BTRs despite discharges remaining constant or even increasing. Blizard and Wohl (1998) note that random events such as tree fall into the channel can also explain BTR variation, however such events did not occur during the Toots Cr experiments.

CONCLUSIONS

Unit BTRs range from 3.5×10^{-6} to 3.3×10^{-2} kg/sec/m during the five events and are highly variable. BTR behavior is best modeled using discharge magnitude, but this relationship differs significantly between Events 1–3 and the larger Events 4 and 5. BTRs also show positive relationships to both shear stress and stream power, but these relationships are much weaker than the one with discharge.

Variation in BTRs between events at low to moderate hydraulic ranges and the marked differences in peak BTRs between similar events (2 v. 3 and 4 v. 5) are best explained by the evolution and disruption of bed material organization during the events and the influence this has on sediment availability. Neither reductions in finer-sediment amounts in the bed between events, nor flow competency differences appear sufficient to explain these results. Rather it is reasoned that bed restructuring through infilling and tightening (Laronne and Carson 1976) of cobble or boulder clusters during each event reduces BTR response during subsequent events until higher forces levels occur and new, entrainable sediment is exposed.

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